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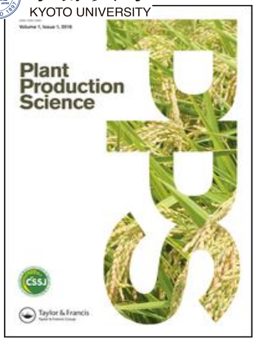


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# Decreasing input–output balance by reducing chemical fertilizer input without yield loss in intensive cropping system in the Coastal Area of southeast Lake Dianchi, Yunnan Province, China

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**ABSTRACT**

Overuse of chemical fertilizer and/or manure in agriculture is a principal factor in water eutrophication in China. Our previous study indicated that reducing chemical fertilizer input effectively decreased the soil nitrogen, phosphorus, and potassium in an intensive vegetable cropping system in the coastal area of southeast Lake Dianchi, China. This study aimed to decrease the input–output balance, namely the nutrient balance between input of fertilizer and output through vegetable harvesting, by reducing chemical fertilizer application without yield loss. A pot experiment was performed using chemical fertilizer with different amounts of N, P, and K on soils from six vegetable fields' representative of the study area. High nitrate concentration in soils 2, 3, and 6 resulted in high N absorption from soil, and low N absorption from chemical fertilizer. Moreover, the responses of dry matter production to N absorbed from chemical fertilizer were less sensitive in soils 2, 3, and 6 than those in the other soils. Accordingly, reducing N input of chemical fertilizer did not decrease total N absorption or dry matter production, which should be the reason why reducing N input of chemical fertilizer did not reduce dry matter production in soils 2, 3, and 6. In the cases of soils 1, 4, and 5, reducing N input of chemical fertilizer reduced dry matter production, owing to lower levels of soil nitrate. This study should be helpful for reducing nutrient surplus from chemical fertilizer in the coastal area of southeast Lake Dianchi and other eutrophic agricultural areas in China.

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Chemical fertilizer; China; Input–output Balance; Pot experiment; Vegetable yield

Over the past three decades, multiple cropping has played a very important role in meeting the rising need for food in China (Yan et al., 2014); however, chemical fertilizer consumption has increased greatly in this intensive cropping system (Ju et al., 2007). Run-off and drainage of excess fertilizers in agriculture is a main source of water eutrophication in China, called non-point source pollution (Sun et al., 2012). Numerous studies have focused on the various nutrient surpluses from agriculture in China, especially in conjunction with intensive vegetable cultivation. For instance, Ju et al. (2006) reported that nitrogen (N), phosphorus (P), and potassium (K) surpluses to greenhouses were more to wheat–maize fields and apple orchards on the north China plain; Chen et al. (2004) evaluated the effect of fertilizer practices on nutrients accumulation in vegetable fields in the Beijing region; Min et al. (2011) determined the N balance and loss in greenhouse in southeastern China; and Moritsuka et al. (2013) reported that accumulation of soluble nutrients in soil was due to over-application of fertilizers in the southeastern basin of Lake Dianchi, China. Calculation of the nutrient input–output balance, namely subtracting the nutrient output through crop harvesting from the nutrient input of fertilizer application, was thought to be one useful method for estimating nutrient surpluses in many studies (He et al., 2007; Ju et al., 2006; Phupaibul et al., 2002). Decreasing nutrient input–output balance means reducing fertilizer application or enhancing output through crop harvesting, which should reduce nutrient surpluses. However, most of former studies only calculated the nutrient input–output balance; whereas, few of them introduced practical measures to reduce nutrient surpluses by decreasing the input–output balance in vegetable fields under intensive cropping.

We conducted a study in the coastal area of southeast Lake Dianchi, Yunnan province, China (Wang et al., 2015). Heavily multiple vegetable cropping in vinyl covered greenhouse is dominant in this area, with large inputs of chemical fertilizer and livestock manure. About 58.2, 72.1, and 20% of N, P, and K were unused by vegetables, inducing nutrient accumulation in soil. By the statistical analysis, we found that it would be more efficient to decrease the input–output balance by reducing input of chemical

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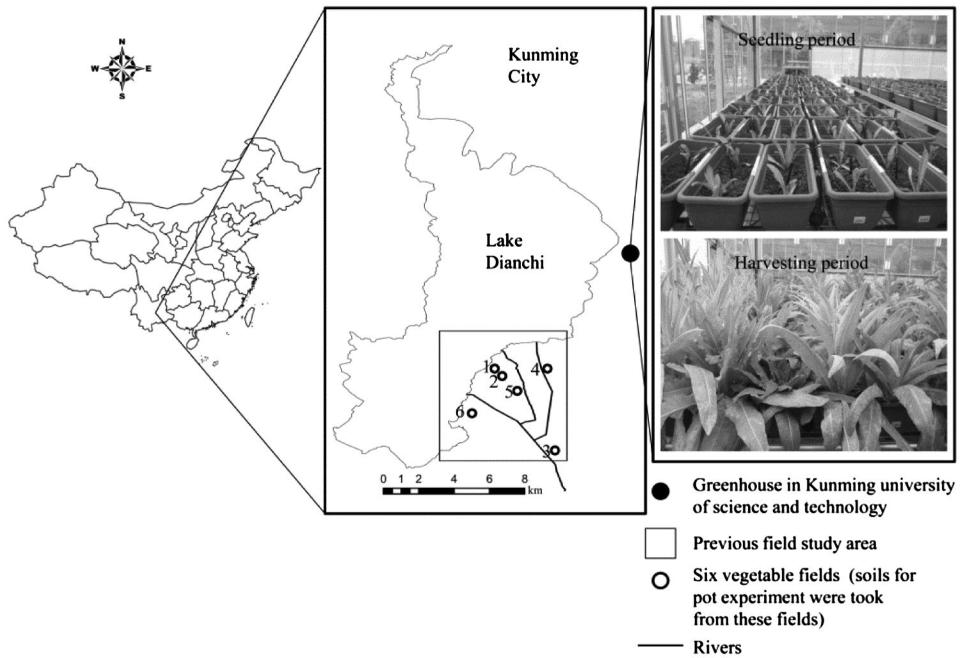


**Figure 1.** Locations of vegetable fields where the soils for pot experiment were taken from.

fertilizer than by reducing input of manure, which was also more efficient than by increasing output.

However, reducing the application of chemical fertilizer might cause reduction in crop yields, damaging farmers' gross income. This study aimed to decrease agricultural pollution by reducing input of chemical fertilizer according to soil characteristics while maintaining vegetable yield. The methods and results of this study should be useful in decreasing environmental risks from intensive vegetable cropping in China.

## Materials and methods

### *Study site*

A previous field study (Wang et al., 2015) was conducted in the coastal area of southeast Lake Dianchi, located southwest of Kunming City, the provincial capital of Yunnan province, in southwest China (24°42′ N, 102°42′ E) (Figure 1). After 2000, the paddy rice-broad bean cropping system of this area was converted to vegetable and flower fields with vinyl houses, demanding more application of fertilizer. The vegetables grown in this area were mainly leafy and cropping intensity in most fields was six or seven crops per year. The nitrate, water-soluble P, and water-soluble K in these vegetable fields were 163, 13, and 97 mg kg$^{-1}$, respectively (Wang et al., 2015).

Soils used for pot experiments were collected from six fields (Figure 1). Field 1 had been converted from a paddy field and was awaiting for vegetable cultivation just before soil collection for the pot experiment, and field 2 was similar but had been cultivated with one crop of vegetables (Table 1). Fields 3 and 6 had been cultivated with vegetables under vinyl houses for five and three years, respectively, representing medium-length vegetable-growing periods. Fields 4 and 5 represented relatively long-length vegetable-growing periods. The cropping intensities of vegetables in fields 3 to 6 ranged from four to seven crops per year, representing the cropping intensities of most vegetable fields in this area. In addition, the variation of soil properties of the six fields reflects fairly well those of the 32 previously surveyed vegetable fields. For instance, soil nitrate in the six fields ranged from 60.2 to 274.1 mg kg$^{-1}$ with an average of 170.8 mg kg$^{-1}$, and those in the 32 fields ranged from 40 to 320 mg kg$^{-1}$ with an average of 163 mg kg$^{-1}$. In summary, the six fields from which soils were taken for pot experiments were representative of the study area.

### *Experimental design*

This experiment was conducted from June 1 to July 15 2012 at a greenhouse in Kunming University of Science and Technology, about 20 km from the previously studied fields. Just after vegetable harvesting by farmers, the surface soil (0–15 cm) was collected from three sites in each field, then uniformly mixed, and 6 kg (dry weight) of soil was loaded into plastic pots (39-cm long, 15 wide, and 13-cm high).

The experimental design is shown in Table 2, and there were three replications of each treatment. The application

**Table 1.** Descriptive statistics of cultivation in vinyl house fields and properties of soils used for pot experiment.

| Variable | Unite | Field 1 | Field 2 | Field 3 | Field 4 | Field 5 | Field 6 |
|---|---|---|---|---|---|---|---|
| Years of vinyl house cultivation | year | 0 | 0 (1 crop) | 5 | 8 | 8 | 3 |
| Cropping intensities of vegetable per year | crop year$^{-1}$ | – | – | 4 | 5 | 7 | 7 |
| *Input of chemical fertilizer per year* | | | | | | | |
| N | g m$^{-2}$ y$^{-1}$ | 29.85 | 17.00 | 74.79 | 142.21 | 262.49 | 107.62 |
| P | g m$^{-2}$ y$^{-1}$ | 5.61 | 7.48 | 16.15 | 28.05 | 51.05 | 18.99 |
| K | g m$^{-2}$ y$^{-1}$ | 10.58 | 14.11 | 10.26 | 52.91 | 96.30 | 94.99 |
| *Input of manure per year* | | | | | | | |
| N | g m$^{-2}$ y$^{-1}$ | .00 | .00 | 10.67 | 85.50 | 164.99 | 33.54 |
| P | g m$^{-2}$ y$^{-1}$ | .00 | .00 | 4.25 | 22.50 | 75.00 | 9.66 |
| K | g m$^{-2}$ y$^{-1}$ | .00 | .00 | 7.46 | 51.75 | 87.00 | 20.88 |
| *Input–output balance (chemical fertilizer + manure)* | | | | | | | |
| N | g m$^{-2}$ y$^{-1}$ | 18.77 | 1.33 | 33.15 | 113.88 | 332.50 | 53.61 |
| P | g m$^{-2}$ y$^{-1}$ | 1.83 | 5.43 | 12.51 | 31.25 | 112.03 | 14.62 |
| K | g m$^{-2}$ y$^{-1}$ | −1.59 | 3.08 | -39.05 | 1.22 | 91.98 | 20.05 |
| *Properties of soils used for pot experiment* | | | | | | | |
| Total N | g kg$^{-1}$ | 2.52 | 3.06 | 1.19 | 2.11 | 1.52 | 2.61 |
| Total C | g kg$^{-1}$ | 25.46 | 27.76 | 8.15 | 16.16 | 12.03 | 24.40 |
| Nitrate | mg kg$^{-1}$ | 60.20 | 185.80 | 288.70 | 94.20 | 121.50 | 274.10 |
| Water-soluble P | mg kg$^{-1}$ | 3.06 | 18.76 | 29.40 | 18.80 | 21.64 | 15.30 |
| Water-soluble K | mg kg$^{-1}$ | 94.40 | 122.00 | 112.40 | 89.10 | 51.40 | 145.80 |
| EC | ms m$^{-1}$ | 130.90 | 154.20 | 69.20 | 98.90 | 39.80 | 57.40 |
| pH | | 7.41 | 7.48 | 7.45 | 7.11 | 7.41 | 7.34 |

*Note*: Content in brackets means only one crop of vegetable had been cultivated before soil collecting for pot experiment. Input of chemical fertilizer per year, input of manure per year, and input–output balance in field one indicate cultivation of paddy rice, and those in other fields indicate cultivation of vegetable.

**Table 2.** Different application amounts of N, P, and K chemical fertilizer.

| Treatment | Amounts of N, P, and K (N-P-K mg pot$^{-1}$) |
|---|---|
| Control (N100-P100-K100) | 879-386-727 |
| Half-N (N50-P100-K100) | 440-386-727 |
| No-N (N0-P100-K100) | 0-386-727 |
| Half-P (N100-P50-K100) | 879-193-727 |
| No-P (N100-P0-K100) | 879-0-727 |
| Half-K (N100-P100-K50) | 879-386-364 |
| No-K (N100-P100-K0) | 879-386-0 |

*Note*: Urea (N ≥ 46.4%), calcium superphosphate ($P_2O_5$ ≥ 16.0%), and potassium chloride ($K_2O$ ≥ 60.0%) were applied as N, P, and K fertilizer, respectively.

of chemical fertilizer for stem lettuce in the control plot was the average from 32 vegetable fields reported in a previous study (Wang et al., 2015), defined as N100-P100-K100. The application amounts of N, P, and K in the control plots were 879, 386, and 727 mg pot$^{-1}$, respectively. The application of N, P, and K to other pots was, respectively, halved or reduced to zero. For instance, N50-P100-K100 means the application of N was halved, andN0-P100-K100 means that the application of N was reduced to zero. Urea (N ≥ 46.4%), calcium superphosphate ($P_2O_5$ ≥ 16.0%), and potassium chloride ($K_2O$ ≥ 60.0%) were applied as N, P, and K fertilizer, respectively, and uniformly applied to the pots before the planting of stem lettuce.

Two seedlings of stem lettuce with normal and equal growth status, a representative vegetable in the study area, were planted in each pot. To avoid the effects from external factors, the positions of the pots were arranged randomly. To control irrigation for each pot as equally as possible, we set a main irrigating pipe with hermetically separated small pipes leading to each pot, and irrigated soils until they reached about pF 2.0 humidity (DIK-8,343, DAIKI, Japan) (Peijnenburg et al., 2000). Forty-five days after seedling transplantation, the stem lettuce was harvested. The growth duration was based on the local farmers' typical management practices.

## *Vegetable and soil analyses*

The aboveground biomass of vegetables was harvested. Vegetable samples were oven-dried at 70 °C to a constant weight and ground until they were fine enough to pass through a 2-mm sieve. The plant sample was digested by the Kjeldahl method, then the concentrations of $NH_4^+$, P, and K were determined, respectively, by the cresol red method (cresol red dissolved in sodium hydroxide solution, then mixed with Hepes; the final solution was used as an indicator per Schulze et al., 1988) with a flow-injection spectrophotometer (WIS-2000, HIRANUMA, Japan); the Vanadomolybdate method (Stuffins, 1967) with a spectrophotometer (U-1500, HITACHI, Japan); and an atomic absorption spectrophotometer alone (AA-7000, SHIMADZU, Japan). The concentration of nitrate ($NO_3^-$) was determined using the Cataldo method (Cataldo et al., 1975) and a spectrophotometer (U-1500, HITACHI, Japan).

The soils used for analysis were extracted from the soils prepared for the pot experiment. Soils were air-dried and ground to pass through a 2-mm sieve. Electrical conductivity (EC) and pH($H_2O$) were measured using a glass electrode after the soil was mixed with distilled water(1:5, w/v). Extraction was used to determine the nitrate and P contents by the Cataldo method (Cataldo et al., 1975) and sulfuric acid-molybdenum method (Martin & Doty, 1949), respectively, using a spectrophotometer (U-1500, HITACHI, Japan). The concentration of K was determined with an atomic absorption spectrophotometer. Total nitrogen (TN) and total carbon (TC) were determined using a mass spectrometer (Delta S, Finnigan MAT, Bremen, Germany) coupled with an elemental analyzer (EA1108, Fisons, Rodano, Milan, Italy) at the Center for Ecological Research, Kyoto University (Kyoto, Japan). The average value of three replications of each treatment was used in the analysis of data.

### Data analyses

N, P, or K balance was calculated as:

N, P, or K balance = N, P, or K input of chemical fertilizer – N, P, or K output by vegetable

The N, P, and K absorbed from sources other than chemical fertilizer was defined as N, P, and K outputs under application by N0-P100-K100, N100-P0-K100, and N100-P100-K0, respectively.

The slope of the linear correlation between input of N chemical fertilizer and output of N reflects the N recovery efficiency. Consequently, N recovery efficiency of chemical fertilizer was calculated as:

$$Nrecovery efficiency of chemical fertilizer = \frac{\frac{Nout_{N100-P100-K100}-Nout_{N0-P100-K100}}{N_{100}}+\frac{Nout_{N50-P100-K100}-Nout_{N0-P100-K100}}{N_{50}}}{2}$$

where $Nout_{N100\text{-}P100\text{-}K100}$, $Nout_{N50\text{-}P100\text{-}K100}$, and $Nout_{N0\text{-}P100\text{-}K100}$ are N outputs under applications by N100-P100-K100, N50-P100-K100, andN0-P100-K100, respectively. P and K recovery efficiencies of chemical fertilizer were calculated by the same methods.

Response of dry matter production to N absorbed from chemical fertilizer was calculated as:

$$DM/Nout = \frac{\frac{DM_{N100-P100-K100}-DM_{N0-P100-K100}}{Nout_{N100-P100-K100}-Nout_{N0-P100-K100}}+\frac{DM_{N50-P100-K100}-DM_{N0-P100-K100}}{Nout_{N50-P100-K100}-Nout_{N0-P100-K100}}}{2}$$

where ⊿DM /⊿Nout stands for variation of dry matter production per unit N absorbed from chemical fertilizer, and $DM_{N100\text{-}P100\text{-}K100}$, $DM_{N50\text{-}P100\text{-}K100}$, and $DM_{N0\text{-}P100\text{-}K100}$ are dry matter production of vegetable under application by N100-P100-K100, N50-P100-K100, and N0-P100-K100, respectively. Responses of dry matter production to P and K absorbed from chemical fertilizer were calculated by the same methods.

The one-way ANOVA was performed to identify the differences among data using SPSS software.

## Results

### The effects of different applications of chemical fertilizer on dry matter production of stem lettuce

The short distance between the greenhouse of pot experiment and the fields ensured that the weather condition at the former was similar to that at the latter. The growth of material plants was normal comparing with that under fields cultivation (Figure 1). Table 3 shows the effects of different applications of chemical fertilizer on dry matter production of stem lettuce. In the case of soil 1, dry matter production of stem lettuce under application of N50-P100-K100, N100-P50-K100, N100-P100-K50, and N100-P100-K0 was not significantly lower than that of N100-P100-K100, respectively. These results indicated that the application of N and P from chemical fertilizer, and the application of K from chemical fertilizer to soil 1 could be reduced to one half and zero, respectively,

**Table 3.** Dry matter productions of stem lettuce under different applications of chemical fertilizer.

| | Dry matter production (g pot$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| Treatment | Soil 1 | Soil 2 | Soil 3 | Soil 4 | Soil 5 | Soil 6 |
| N100-P100-K100 | 27.0$^{a}$ | 15.6$^{a}$ | 22.9$^{a}$ | 36.4$^{a}$ | 22.3$^{a}$ | 16.9$^{a}$ |
| N50-P100-K100 | 21.9$^{ab}$ | 19.2$^{a}$ | 31.3$^{a}$ | 41.5$^{a}$ | 19.2$^{a}$ | 13.4$^{a}$ |
| N0-P100-K100 | 13.5$^{b}$ | 18.5$^{a}$ | 29.8$^{a}$ | 21.5$^{b}$ | 12.1$^{b}$ | 15.7$^{a}$ |
| N100-P100-K100 | 27.0$^{a}$ | 15.6$^{a}$ | 22.9$^{a}$ | 36.4$^{a}$ | 22.3$^{a}$ | 16.9$^{a}$ |
| N100-P50-K100 | 19.9$^{a}$ | 19.4$^{a}$ | 19.3$^{a}$ | 34.0$^{a}$ | 20.6$^{a}$ | 15.5$^{a}$ |
| N100-P0-K100 | 4.4$^{b}$ | 11.3$^{a}$ | 29.5$^{a}$ | 37.7$^{a}$ | 18.4$^{a}$ | 19.6$^{a}$ |
| N100-P100-K100 | 27.0$^{a}$ | 15.6$^{a}$ | 22.9$^{a}$ | 36.4$^{a}$ | 22.3$^{a}$ | 16.9$^{a}$ |
| N100-P100-K50 | 19.5$^{a}$ | 20.4$^{a}$ | 25.9$^{a}$ | 32.1$^{a}$ | 17.9$^{ab}$ | 13.2$^{a}$ |
| N100-P100-K0 | 17.5$^{a}$ | 18.2$^{a}$ | 22.2$^{a}$ | 32.8$^{a}$ | 15.1$^{b}$ | 19.4$^{a}$ |

*Note*: Soils 1–6 mean the soils took from the fields 1–6, respectively. Different letters within a column indicate significant differences ($P < .05$) by LSD significant difference test.

without yield loss. In the case of soil 4, dry matter production under application of N0-P100-K100 was lower than those under N50-P100-K100 and N100-P100-K100. In the case of soil 5, dry matter productions under application of N50-P100-K100, N100-P50-K100, N100-P0-K100, and N100-P100-K50 were not significantly lower than that of N100-P100-K100, respectively. These results indicated that the application of N and K from chemical fertilizer to soil 5 could be halved, and the application of P from chemical fertilizer could be eliminated without yield loss. In the cases of soils 2, 3, and 6, there were no significant differences among the dry matter productions under different applications of N, P, and K chemical fertilizer, indicating that the application of N, P, and K from chemical fertilizer could all be reduced to zero without yield loss.

### *The effects of different applications of chemical fertilizer on N, P, and K outputs*

Decreasing application of N chemical fertilizer induced a significant decrease in N absorbed by stem lettuce in soils 1, 4, and 5 (Table 4). Decreasing application of P chemical fertilizer induced a significant decrease in P absorbed by stem lettuce grown in soil 1. Decreasing application of K chemical fertilizer induced a significant decrease in K absorbed by stem lettuce grown in soils 1 and 5. For other soils, there were no significant differences in the nutrient absorptions under different applications of chemical fertilizer.

### *The effects of different applications of chemical fertilizer on N, P, and K balances*

Table 5 shows the N, P, and K balances under different applications of chemical fertilizer; the negative values in the tables indicate that the amounts of N, P, and K absorbed by stem lettuce were higher than the inputs of N, P, and K. Except for the cases of soils 4 and 6 under the application of N50-P100-K100, the N balances under the application of N50-P100-K100 and N0-P100-K100 were significantly lower than those of N100-P100-K100, respectively. Except for the case of soil 3 under the application of N100-P50-K100, the P balances under the application of N50-P100-K100 and N0-P100-K100 were significantly lower than that of N100-P100-K100, respectively. In the case of K, the K balances in soils 1 and 5 under N100-P100-K0, and soils 2 and 4 under the application of N100-P100-K50 and N100-P100-K0 were significantly lower than that of N100-P100-K100, respectively.

**Table 4.** N, P, and K outputs under different application of chemical fertilizer.

| Treatment | Output by vegetable (mg pot$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil 1 | Soil 2 | Soil 3 | Soil 4 | Soil 5 | Soil 6 |
| | | | N | | | |
| N100-P100-K100 | 402.3$^{a}$ | 427.5$^{a}$ | 666.5$^{a}$ | 732.0$^{a}$ | 506.5$^{a}$ | 778.1$^{a}$ |
| N50-P100-K100 | 299.0$^{ab}$ | 524.6$^{a}$ | 767.0$^{a}$ | 559.4$^{ab}$ | 476.0$^{a}$ | 595.8$^{a}$ |
| N0-P100-K100 | 172.1$^{b}$ | 478.3$^{a}$ | 776.0$^{a}$ | 268.2$^{b}$ | 299.0$^{b}$ | 523.9$^{a}$ |
| | | | P | | | |
| N100-P100-K100 | 161.6$^{a}$ | 151.1$^{a}$ | 215.8$^{a}$ | 291.8$^{a}$ | 223.7$^{a}$ | 165.2$^{a}$ |
| N100-P50-K100 | 115.6$^{b}$ | 161.2$^{a}$ | 169.7$^{a}$ | 281.0$^{a}$ | 227.2$^{a}$ | 156.1$^{a}$ |
| N100-P0-K100 | 29.3$^{c}$ | 99.6$^{a}$ | 254.1$^{a}$ | 303.4$^{a}$ | 186.0$^{a}$ | 147.6$^{a}$ |
| | | | K | | | |
| N100-P100-K100 | 1075.1$^{a}$ | 733.1$^{a}$ | 1015.8$^{a}$ | 927.9$^{a}$ | 1035.3$^{a}$ | 1335.4$^{a}$ |
| N100-P100-K50 | 835.1$^{b}$ | 768.6$^{a}$ | 950.3$^{a}$ | 951.8$^{a}$ | 916.6$^{ab}$ | 875.3$^{a}$ |
| N100-P100-K0 | 588.8$^{c}$ | 622.4$^{a}$ | 710.6$^{a}$ | 738.4$^{a}$ | 705.6$^{b}$ | 999.3$^{a}$ |

*Note*: Soils 1–6 mean the soils took from the fields 1–6, respectively. Different letters within a column indicate significant differences ($P < .05$) by LSD test.

**Table 5.** N, P, and K balances under different application of chemical fertilizer.

| Treatment | Balance (mg pot$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil 1 | Soil 2 | Soil 3 | Soil 4 | Soil 5 | Soil 6 |
| | | | N | | | |
| N100-P100-K100 | 476.7$^{a}$ | 451.5$^{a}$ | 212.5$^{a}$ | 147.0$^{a}$ | 372.5$^{a}$ | 100.9$^{a}$ |
| N50-P100-K100 | 141.0$^{b}$ | −84.6$^{b}$ | −327.0$^{b}$ | −119.4$^{ab}$ | −36.0$^{b}$ | −155.8$^{a}$ |
| N0-P100-K100 | −172.1$^{c}$ | −478.3$^{b}$ | −776.0$^{c}$ | −268.2$^{b}$ | −299.0$^{c}$ | −523.9$^{b}$ |
| | | | P | | | |
| N100-P100-K100 | 224.4$^{a}$ | 234.9$^{a}$ | 170.2$^{a}$ | 94.2$^{a}$ | 162.3$^{a}$ | 220.8$^{a}$ |
| N100-P50-K100 | 77.4$^{b}$ | 31.8$^{b}$ | 23.3$^{a}$ | −88.0$^{b}$ | −34.2$^{b}$ | 36.9$^{b}$ |
| N100-P0-K100 | −29.3$^{c}$ | −99.6$^{b}$ | −254.1$^{b}$ | −303.4$^{c}$ | −186.0$^{c}$ | −147.6$^{c}$ |
| | | | K | | | |
| N100-P100-K100 | −348.1$^{a}$ | −6.1$^{a}$ | −288.8$^{a}$ | −200.9$^{a}$ | −308.3$^{a}$ | −608.4$^{a}$ |
| N100-P100-K50 | −471.1$^{ab}$ | −404.6$^{b}$ | −586.3$^{a}$ | −587.8$^{b}$ | −552.6$^{ab}$ | −511.3$^{a}$ |
| N100-P100-K0 | −588.8$^{b}$ | −622.4$^{b}$ | −710.6$^{a}$ | −738.4$^{b}$ | −705.6$^{b}$ | −999.3$^{a}$ |

*Note*: Soils 1–6 mean the soils took from the fields 1–6, respectively. Different letters within a column indicate significant differences ($P < .05$) by LSD difference test.

### *Relationships between nutrient in soil, nutrient absorbed from sources other than chemical fertilizer, nutrient recovery efficiency from chemical fertilizer, and response of dry matter production to nutrient absorbed from chemical fertilizer*

Figure 2(a) shows a significant correlation between nitrate in soil and N absorbed from sources other than chemical fertilizer by stem lettuce. The correlations between soil P and P absorbed from sources other than chemical fertilizer, and soil K and K absorbed from sources other than chemical fertilizer were not significant (Figure 2(b) and (c)).

The correlation between N absorbed from sources other than chemical fertilizer and N recovery efficiency of chemical fertilizer was not significant (Figure 3(a)), but the P value was .063, which is very close to .05. The correlation between P absorbed from sources other than chemical fertilizer and P recovery efficiency from chemical fertilizer was significantly negative (Figure 3(b)). The correlation between K absorbed from sources other than chemical fertilizer and K recovery efficiency of chemical fertilizer was not significant (Figure 3(c)).

The correlation between N absorbed from sources other than chemical fertilizer and response of dry matter production to N absorbed from chemical fertilizer was significant (Figure 4(a)). The correlations between P absorbed from sources other than chemical fertilizer and response of dry matter production to P absorbed from chemical fertilizer, and K absorbed from sources other than chemical fertilizer and response of dry matter production to K absorbed from chemical fertilizer were not significant (Figure 4(b) and (c)).

## Discussion

### *Decreasing N, P, and K balances without yield loss*

While reducing agricultural pollution by limiting chemical fertilizer input is important, maintaining yield is also important. Table 6 summarizes the data in Tables 3 and 5, reflecting the application methods in the six soils that could decrease the N, P, or K balances by reducing input of chemical fertilizer without resulting in yield loss. In Table 6, the effect of reduced N, P and K was investigated separately. Since these would lower the soil nutrient levels, they would help to reduce non-point source pollution in the short term.

In the case of soil 1, there was a contradiction between reducing the input of N or P from chemical fertilizer without yield loss and decreasing the input–output balance of N or P, respectively. Under N0-P100-K100 or N100-P0-K100, the input–output balance of N or P significantly decreased, but the dry matter production fell. When the N or P input was reduced by half, productivity was maintained, but 141.0 mg pot$^{-1}$ N or 77.4 mg pot$^{-1}$ P remained (Tables 3 and 5). Yields were preferentially considered in this situation. In the case of soil 4, since the dry matter production under N0-P100-K100 was lower than those under N50-P100-K100 and N100-P100-K100, reducing N input to zero was not appropriate for maintaining yield in soil 4. In the case of soil 5, halving N input, reducing P input to zero, or halving K input was appropriate for decreasing the N, P, or K balance without yield loss, respectively. In the case of other soils, reduction in all the N, P, or K input for one season was appropriate. In addition, this result is

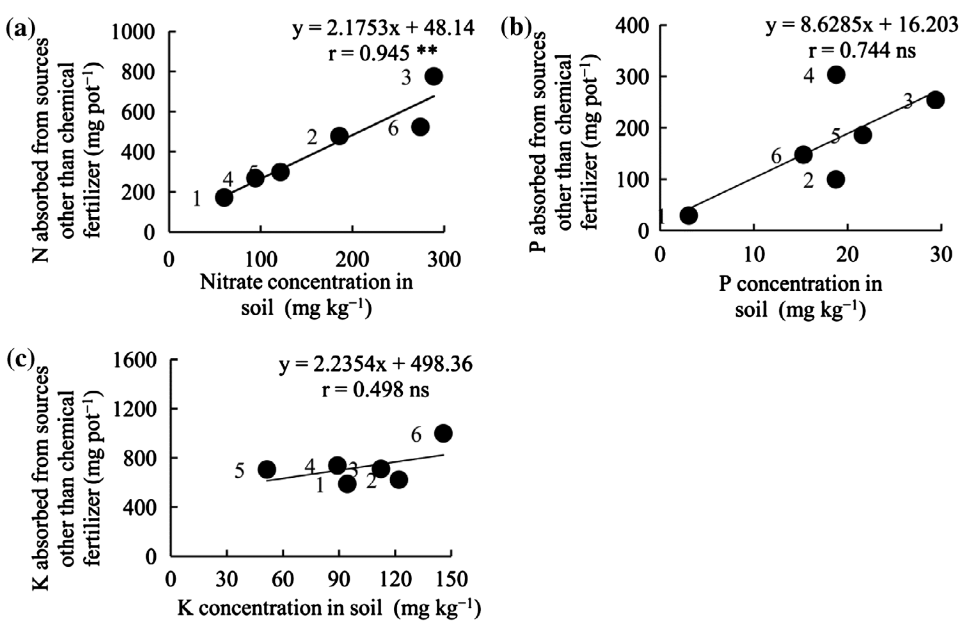


**Figure 2.** Relationships between soil Nitrate, P, and K and N, P, and K absorbed from sources other than chemical fertilizer by stem lettuce. Numbers on the left of dots represent the numbers of the soils for pot experiment. *Note*. **significant at $P < .01$; ns, not significant.

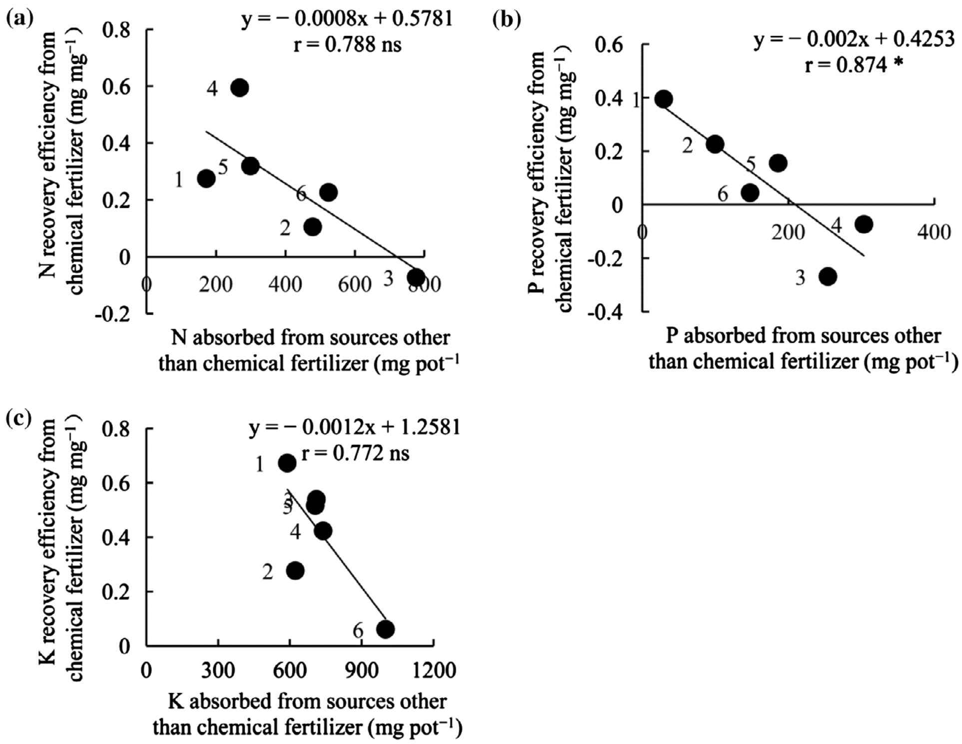


**Figure 3.** Relationships between N, P, and K absorbed from sources other than chemical fertilizer and N, P, and K recovery efficiencies of chemical fertilizer. Numbers on the left of dots represent the numbers of the soils for pot experiment. *Note*. *significant at $P < .05$; ns, not significant.

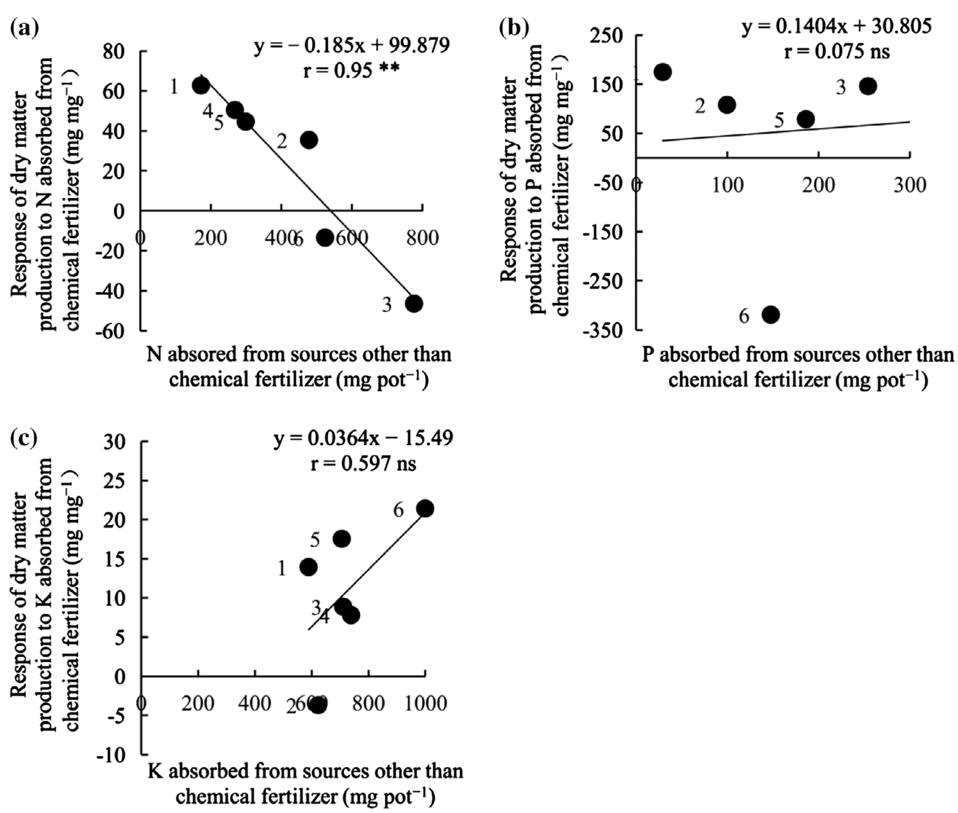


**Figure 4.** Relationships between N, P, and K absorbed from sources other than chemical fertilizer and responses of dry matter production to N, P, and K absorbed from chemical fertilizer. Numbers on the left of dots represent the numbers of the soils for pot experiment. *Note*. **significant at $P < .01$; ns, not significant.

**Table 6.** Percentage reduction of N, P, and K inputs without yield loss.

| | Soil 1 | Soil 2 | Soil 3 | Soil 4 | Soil 5 | Soil 6 |
|---|---|---|---|---|---|---|
| N | 50 | 100 | 100 | 50 | 50 | 100 |
| P | 50 | 100 | 100 | 100 | 100 | 100 |
| K | 100 | 100 | 100 | 100 | 50 | 100 |

*Notes*: Soils 1 to 6 mean the soils took from the fields 1–6, respectively. The effect of reduced N, P, and K was investigated separately.

helpful for increasing farmers' profits by saving expenses on chemical fertilizer.

The input–output balance is relevant to both of soil recharge and reducing nutrient accumulation in soil. In the case of infertile soil, decreasing the input–output balance to a negative value will make the soil more infertile, unsustainable in terms of productivity. For instance, soil 1 was not excessively fertile in nitrate. In this situation, some soil recharge was thought to be more important, thus, the balance under application of N50-P100-K100, 141-mg pot$^{-1}$, was more appropriate than that under application of N0-P100-K100, −172.1-mg pot$^{-1}$. For excessively fertile soil, reducing nutrient accumulation is principal, and a negative input–output balance will mitigate agricultural non-point source pollution.

### *The reason for different responses of nutrient absorption to reduction in chemical fertilizer input*

First, the effects of soil nutrients on nutrients absorption from sources other than chemical fertilizer were considered. The significant correlation between nitrate in soil and N absorbed from sources other than chemical fertilizer suggesting that under the complete elimination of N chemical fertilizer, N absorbed by stem lettuce mainly originated from the nitrate in soil (Figure 2(a)). The results of Figures 2(b) and (c) suggested that the absorbed P and K that did not come from fertilizer originated from sources and mechanisms other than soil P and K. The size of pots was designed basing on the cropping density of vegetable under field cultivation. Moreover, local stem lettuce is a kind of short-term varieties (growth duration under field cultivation is 30 to 50 days) and the root-system under field cultivation and pot cultivation is relatively short. The size of pots should be enough for normal growth of stem lettuce. Furthermore, there is no significant difference between nitrate output by stem lettuce in pots and that under field cultivation (data not shown). Consequently, the nitrate availability for stem lettuce in pots should not be affected by the root restricting, and the relationship in Figure 2 should be applicable to the field condition.

Next, the effects of the nutrient absorbed from sources other than chemical fertilizer on nutrient recovery efficiency were considered. When the N absorbed from sources other than chemical fertilizer increased, the N recovery efficiency from chemical fertilizer seemed to decrease (Figure 3(a)). The N absorbed from sources other than chemical fertilizer mainly originated from soil nitrate (Figure 2(a)), thus N absorption from soil might be complementary to N absorption from chemical fertilizer by vegetables. It was considered that high N recovery efficiency of chemical fertilizer greatly decreased the absorption of N chemical fertilizer by reducing the amount of input of N chemical fertilizer. N absorbed from soil was lower in soils 1, 4, and 5 than those in other fields (Figure 2(a)), owing to there being relatively less nitrate in those soils (Table 1). In this situation, the N recovery efficiency of chemical fertilizer by stem lettuce was higher in soils 1, 4, and 5 than those in soils 2, 3, and 6 (Figure 3(a)), indicating that if the amount of input of N chemical fertilizer was reduced in soils 1, 4, and 5, the total amount of N absorbed would easily decrease.

P absorbed from other sources was not affected by soil P (Figure 2(b)); thus, soil P did not affected the P recovery efficiency of chemical fertilizer by stem lettuce. As in the case of K, soil K did not affected the K recovery efficiency of chemical fertilizer by stem lettuce (Figure 2(c) and 3(c)).

The response of dry matter production to N absorbed from chemical fertilizer was negatively associated with N absorbed from sources other than chemical fertilizer, namely from soil (Figure 4(a)). The less N absorbed from soil, the more sensitively dry matter production responded to N absorbed from chemical fertilizer.

As mentioned above, reducing the amount of chemical fertilizer application should decrease N absorbed from chemical fertilizer by stem lettuce in soils 1, 4, and 5; moreover, the responses of dry matter production to N absorbed from chemical fertilizer were more sensitive in these soils. Accordingly, reducing a certain input amount of N chemical fertilizer would more easily decrease the dry matter production in soils 1, 4, and 5. In the cases of soils 2, 3, and 6, owing to the high concentration of soil nitrate, the N input–output balance could be decreased by reducing N input of chemical fertilizer without yield loss. These soils were fertile in nitrate (Table 1), and decreasing N balance to a negative value was conducive to mitigation of eutrophication.

Relationships between P and K absorbed from sources other than chemical fertilizer and the responses of dry matter production to P and K absorbed from chemical fertilizer were not significant (Figure 4(b) and (c)). The method of analyzing the effect of reducing N fertilizer on dry matter production was not thought to be suited to P and K.

### *Application of this study*

Zhang et al. (2007) indicated that from 1999 to 2005 the P concentration in Lake Dianchi decreased from .331 to .187 mg $L^{-1}$, and the contribution of N to the eutrophication was larger than that of P based on the total pollution analysis and statistical analysis from several years water monitoring data. This pot experiment is helpful to reduce the N burden from agriculture.

Given China's trend toward intensive agriculture (Ju et al., 2009), this study should have universal application. For instance, Shouguang City of Shandong province is the largest greenhouse vegetable production base in China, and vegetable cropping is intensive with large inputs of fertilizer. As documented in 2010, the average contents of available N and available K in the soil were 248 and 486 mg $kg^{-1}$, respectively, and the available P was 135 and 377 mg $kg^{-1}$; all three are much more than vegetables require (Yu et al., 2010). Thus, the same pot experiment is thought to be suitable for reducing nutrient balance without yield loss in the area. To get a more exact optimal amount of chemical fertilizer, greater variety of application amounts of chemical fertilizer is needed.

## Conclusions

We collected soils from six fields representing the characteristic soil and cultivation treatments in the study area, and then performed a pot experiment applying chemical fertilizer with different amounts of N, P, and K. Reducing N, P, or K chemical fertilizer decreased the dry matter production in soils 1, 4, and 5. Reducing inputs of N and P chemical fertilizer decreased the N and P input–output balance in all soils, and reducing the input of K chemical fertilizer decreased the K input–output balance in soils 1, 2, 4, and 5. We summarized the vegetable dry matter production and input–output balances under these treatments, and found the appropriate percentages by which N, P, or K chemical fertilizer could be reduced for each soil and still maintain yields. Decreasing the input–output balance to a negative value in infertile soil will make soil more infertile, unsustainable in terms of productivity. But for fertile soil, decreasing the input–output balance to a negative value will reduce nutrient accumulation in soil while maintaining productivity.

Then, we discussed the reasons why the dry matter production decreased under lower chemical fertilizer inputs in some soils. The presence of low nitrate concentration in soils 1, 4, and 5 resulted in low N absorption from sources other than chemical fertilizer and high N absorption from chemical fertilizer. Moreover, the responses of dry matter production to N absorbed from chemical fertilizer were more sensitive in these soils. Accordingly, the dry matter production was more easily affected by reducing N chemical fertilizer in these soils. However, the method of analyzing the effect of reducing N chemical fertilizer on dry matter production was not suitable for the analysis of P and K.

Since intensive cropping is indispensable in China, decreasing the input–output balance by reducing the application of chemical fertilizer should help decrease nutrient surpluses and mitigate non-point source pollution from agriculture. The method of this study is easy to perform and should have universal application in other eutrophic agricultural areas in China.

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